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Advanced Mark-BW Mechanical Design Topical

NRC and Framatome ANP

June 18, 2002

Framatome ANP Non-Proprietary

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OVERVIEW

> Advanced Mark-BW Design Features

> Mark-BW Operating Experience

> Advanced Mark-BW LTA Program

> Design Evaluation

> Conclusions

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Mark-BW to Advanced Mark-BW Design Evolution

> Features implemented on a plant-specific basis since the NRC review and approval of BAW-10172P

- Debris filter bottom nozzle
- Reduction in number of grid restraining guide thimbles from 12 to 8
- Low pressure drop top nozzle

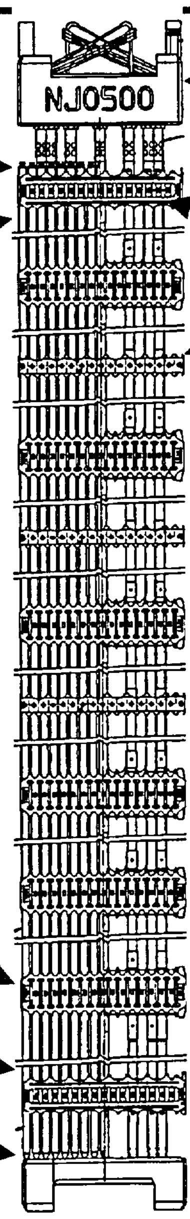
> Features related to the use of M5 material that were reviewed and approved by the NRC in BAW-10227P-A

- M5 fuel rod cladding
- M5 guide thimbles
- M5 instrument tube sheath
- M5 intermediate grids

> Features that are new and specific to the Advanced Mark-BW design

- M5 Mid-span mixing grids (MSMGs)
- Quick disconnect (QD) top nozzle connection

Advanced Mark-BW Design Features



M5™ Design Features Implementation Schedule

Fuel Rods - Fall 2001
Guide Tubes - Fall 2001

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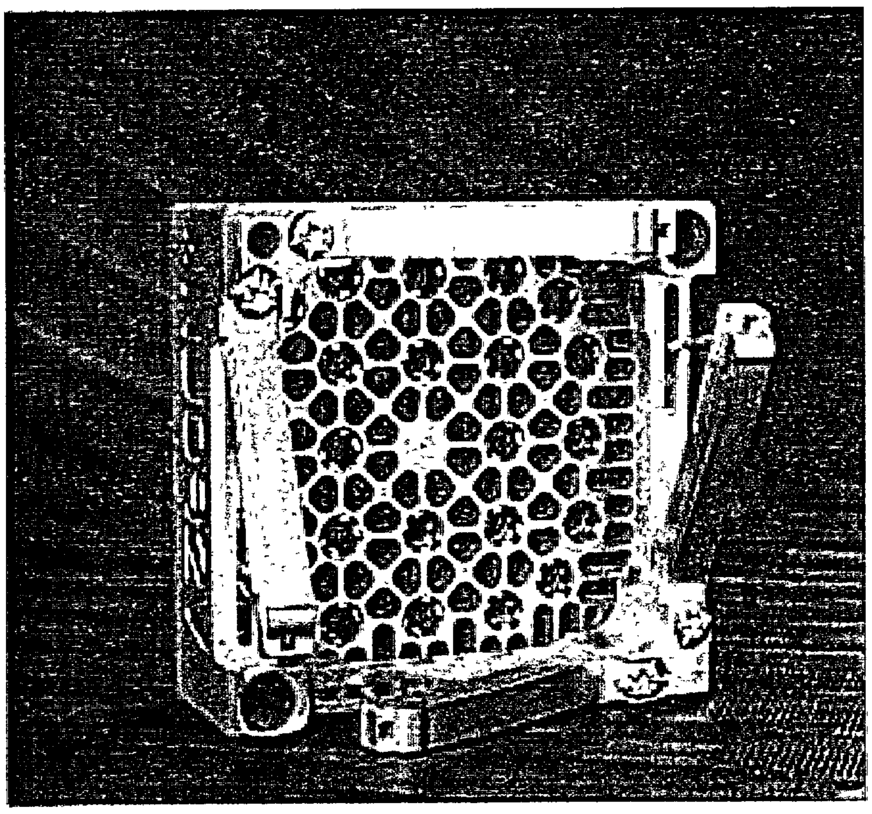
Advanced Mark-BW (17x17) Top Nozzle



> Design Features
  - Low pressure drop
  - Optimized Inconel 718 leaf springs
  - Inconel 718 clamp screws

> U.S. Operational History
  - Introduced February 2000

[ ]

> Standard supply in France

> QD connection features verified with LTA program

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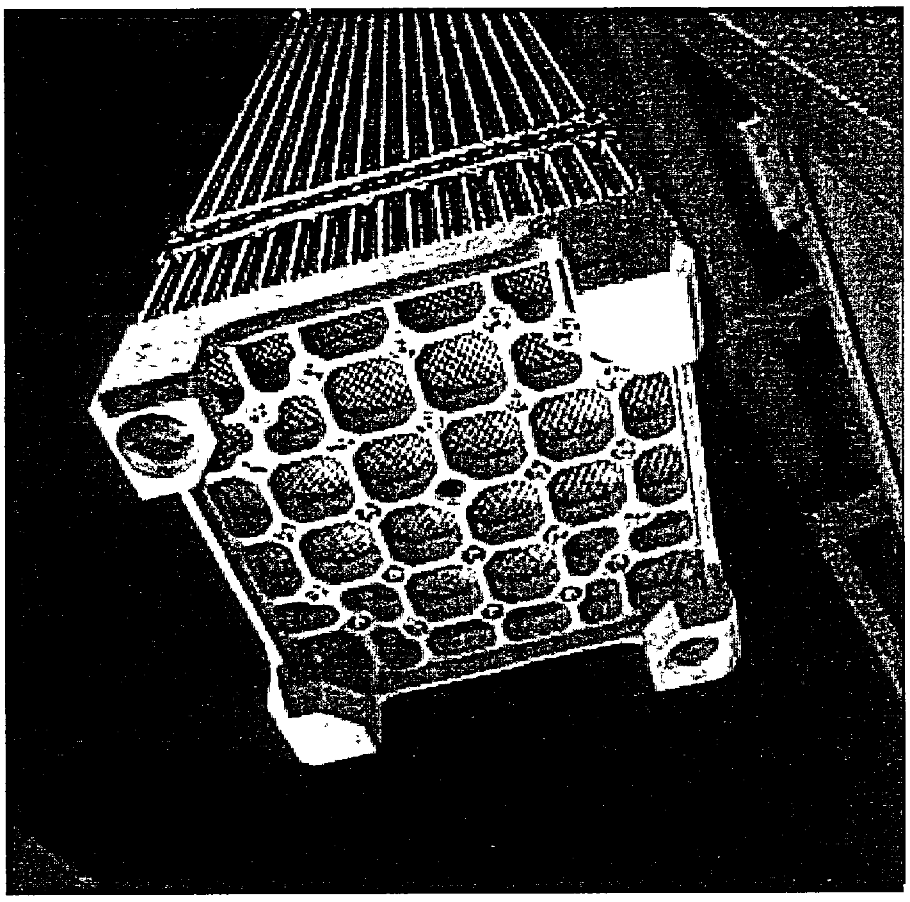
TRAPPER™ Bottom Nozzle



> Provides superior debris protection
  - No debris failures since introduction
  - Pressure drop equivalent to traditional debris filters

> U.S. Operational History
  - Introduced in January 1996

[ ]

> Standard supply in France

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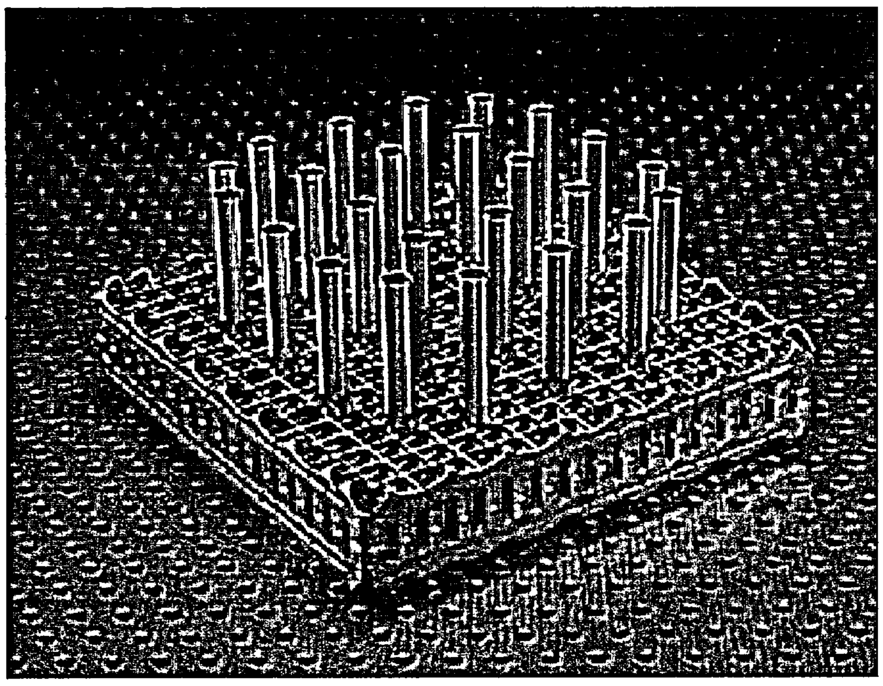
Mark-BW (17x17) Structural Grids



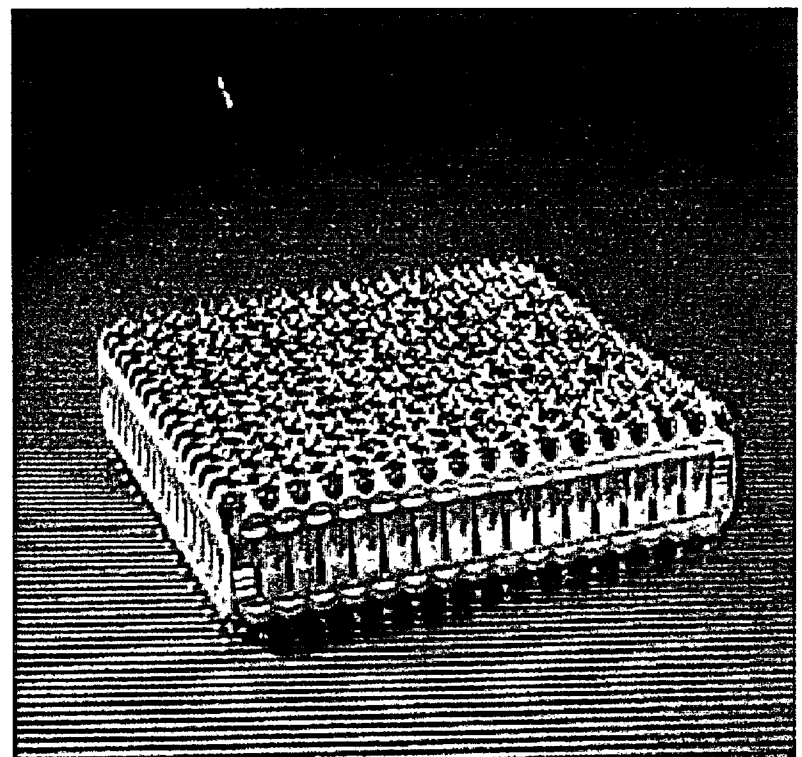
Inconel 718 End Grid Assembly

> U.S. Operational History

- End grid and intermediate grids introduced in original Mark-BW design in 1987

- M5 grid is same grid as zircaloy 4 grid
- Basically same material properties
- Low corrosion

M5 Intermediate Grid



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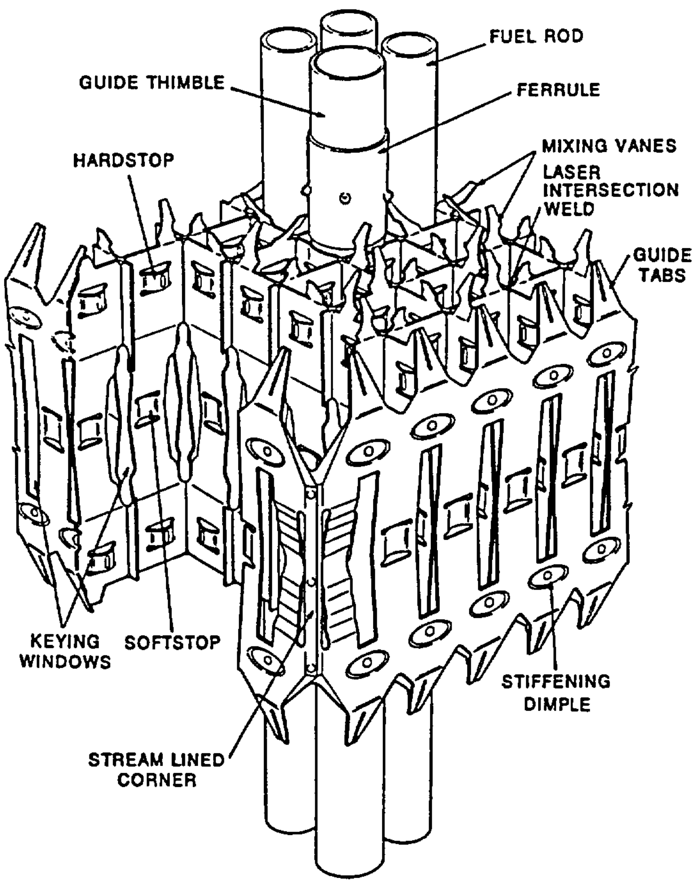
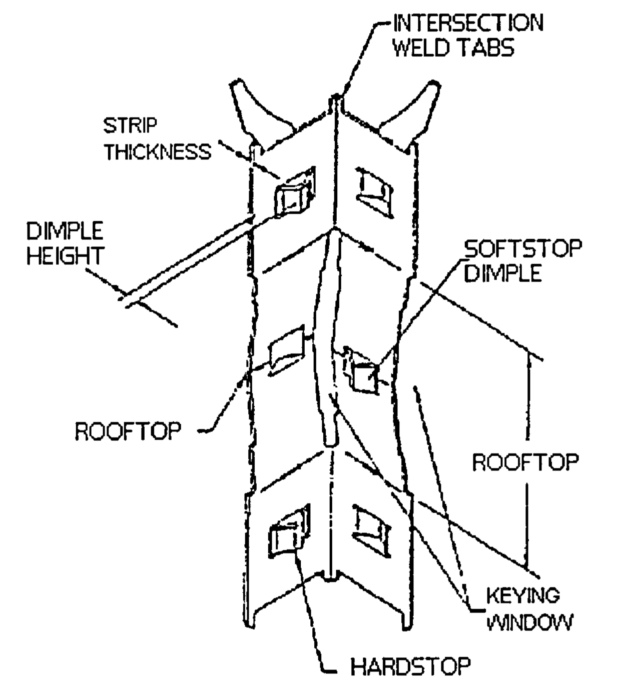
Mark-BW (17x17) Intermediate Grid Features

- High CHF performance
- Floating intermediate grids
- Keyed spacer grids



Grid Details (Including Restraint Features)

Inner Grid Strip Features



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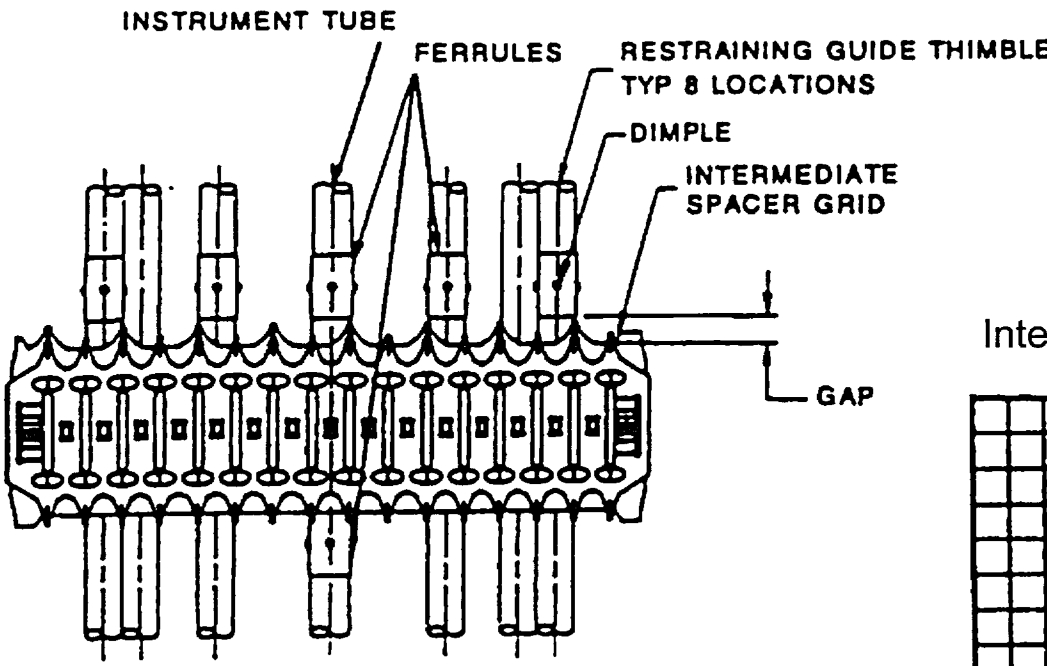
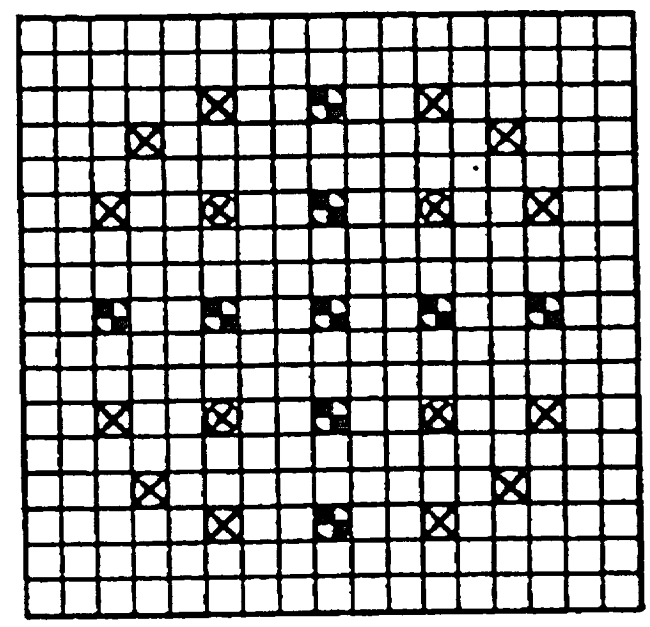
Mark-BW (17x17) Intermediate Grid Restraint



Intermediate Grid Restraining GT Locations



Mid-span Mixing Grids Restraining GT Locations

> Grid restraint design remains unchanged since 1992 [ ]
  - Number of grid restraint guide thimble locations reduced from 12 to 8

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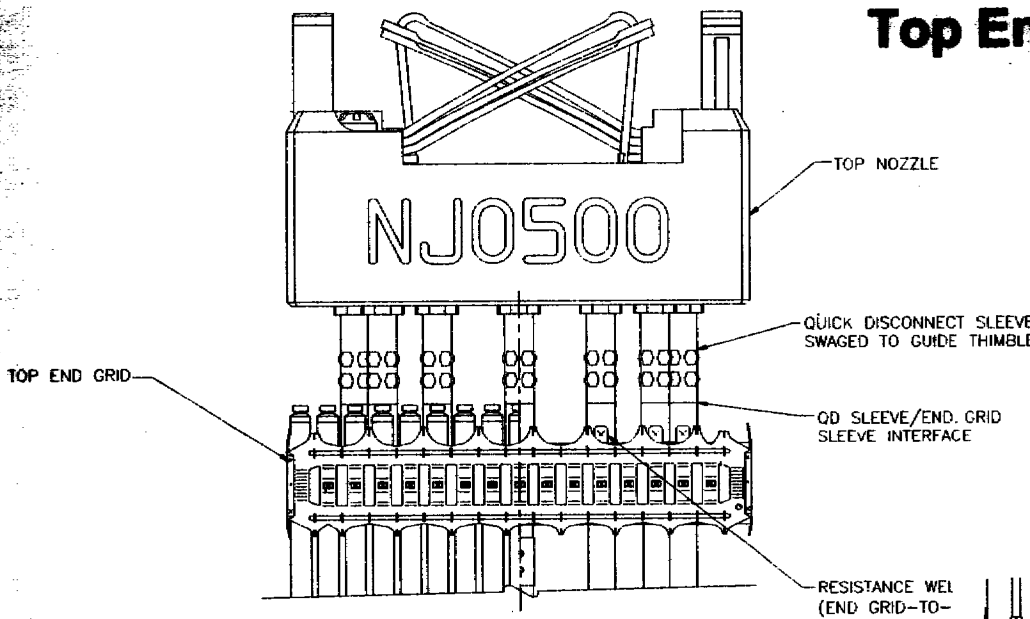
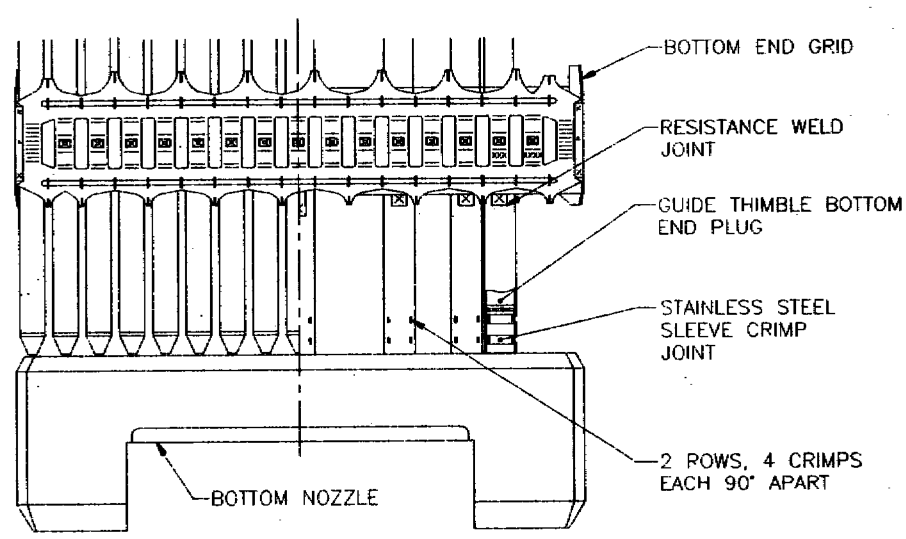
Mark-BW (17x17) End Grid Restraint

Top End Grid Restraint

> Same end grid restraint design

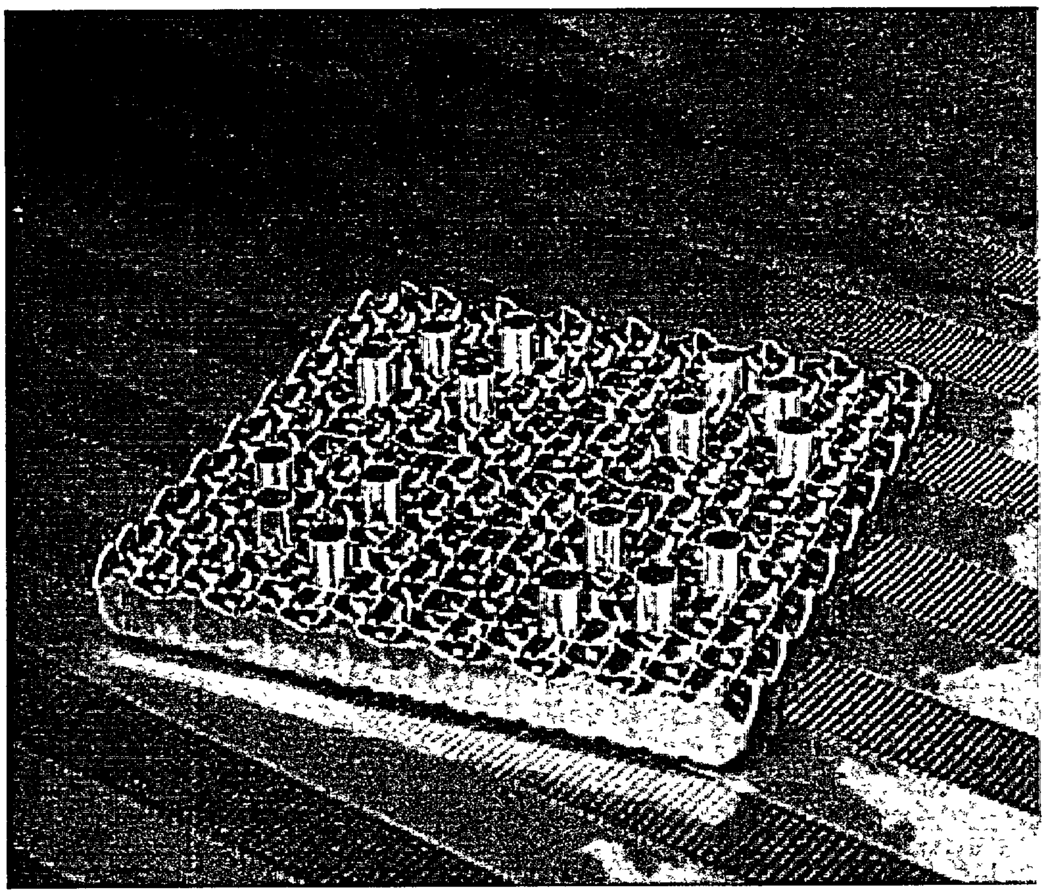
- Accommodates quick disconnect top nozzle feature





Bottom End Grid Restraint

Mark-BW (17x17) Mid-Span Mixing Grid



> MSMG verified with LTA program
> CHF performance topical approved
  - BAW-10199P-A Addendum 2

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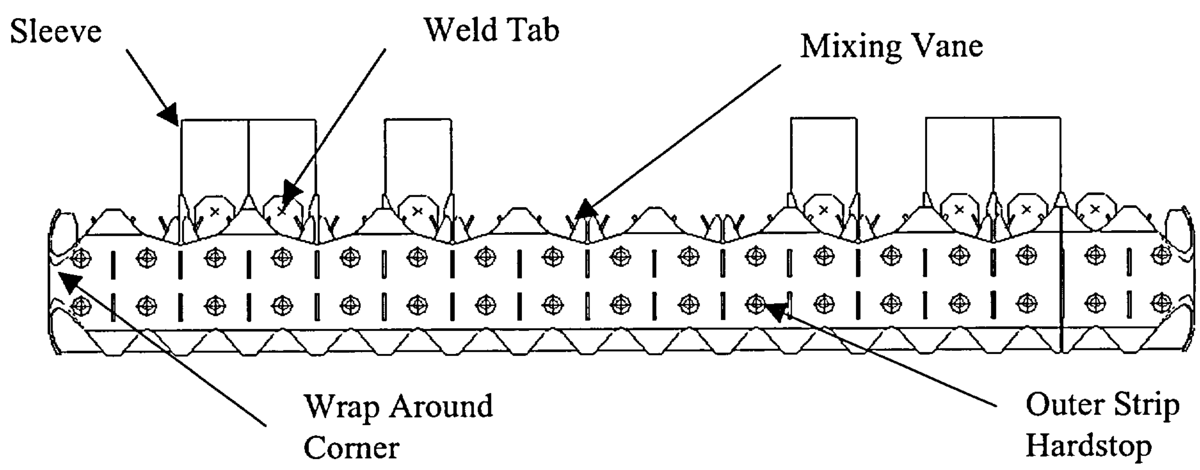
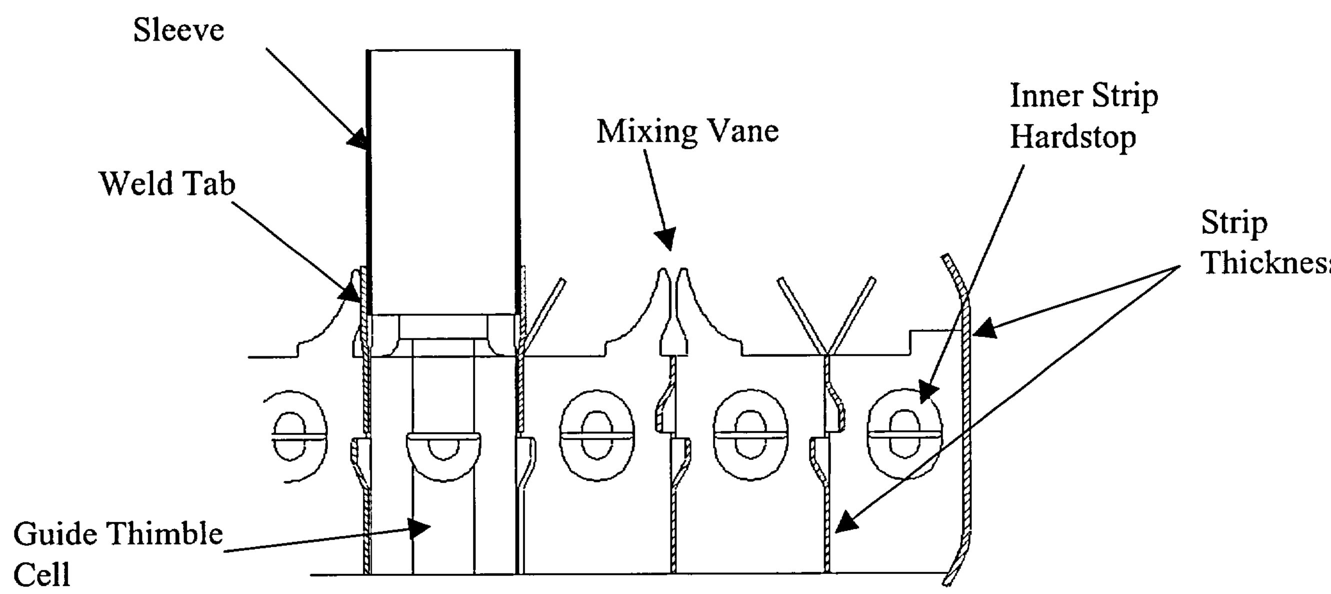
Mark-BW (17x17) MSMG Details





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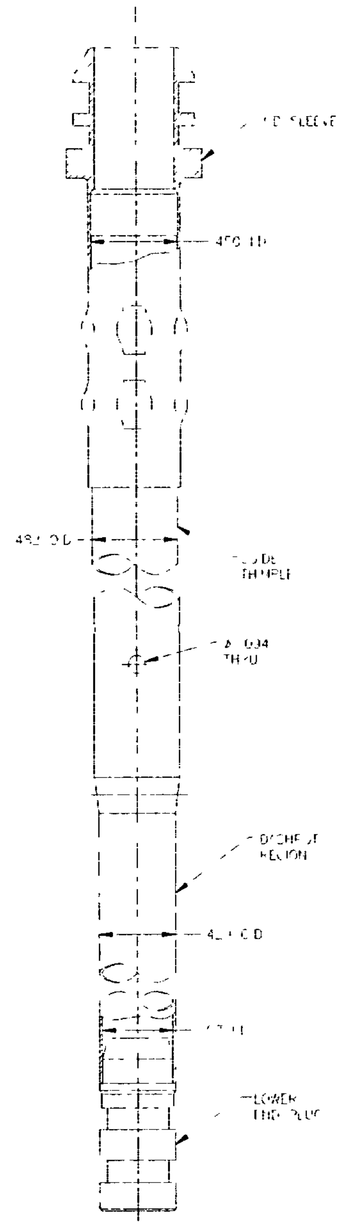
Advanced Mark-BW (17x17) Guide Thimble Assembly



> Same guide thimble dimensions
> Incorporates Quick Disconnect (QD) features
> QD sleeve material is 304L
  - Not susceptible to stress corrosion cracking
  - Fabrication process does not introduce heat source to sensitize material

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Advanced Mark-BW (17x17) Fuel Rod

Fuel Rod Parameters	Mark-BW	Advanced Mark-BW
Clad Material	SRA Zircaloy-4 or M5 Alloy	M5 Alloy
Fuel Rod Length, in	151.80	152.16
Cladding OD, in	0.374	0.374
Cladding Thickness, in	0.024	0.0225
Cladding ID, in	0.326	0.329
Clad-to-Pellet Gap, in	0.0065	0.0065
Fuel Pellet OD, in	0.3195	0.3225
Plenum Springs	Top and Bottom	Top

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Mark-BW Fuel Operating Experience

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Framatome ANP PWR Fuel Burnup Summary As Of 12/01

Framatome ANP PWR Fuel Burnup Summary As Of 12/01

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Framatome ANP PWR Fuel Burnup Summary As Of 12/01

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Failure Rate for Mark-BW (17x17) Fuel By Year Of Manufacture

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Lead Test Assembly Program

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Lead Test Assembly Program

> Advanced Mark-BW/X1 – North Anna

■ Objectives

- Confirm operating performance of design features (MSMG's and Quick Disconnect Top Nozzle)
- Provide high/extended burnupp data on M5™

■ Scope/Status

- 4 LTAs successfully completed 3-18 month cycles of irradiation in North Anna 1 (56.6 GWd/mtU rod burnup)
- PIE completed January 2002
- Scheduled for re-insertion for a fourth cycle in North Anna 2
- PIE - Fall 2004
  - ~73 GWd/mtU fuel rod burnup
- Potential Hot Cell
  - 2003 (3 cycles)
  - 2005-2006 (4 cycles)

[ ]

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Extensive PIE Scope for LTAs

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LTA Summary

> *After three cycles of irradiation in North Anna unit 1, the Advanced Mk-BW lead assemblies performed exceptionally well*

> *Low axidation, growth and deformation evaluations indicate that a fourth cycle of exposure is easily accommodated*

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Design Evaluation

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Advanced Mark-BW Design Evaluation

> Demonstrates that the fuel assembly satisfies the requirements outlined in Section 4.2 of the Standard Review Plan, NUREG-0800

> **Fuel System Damage Criteria**

- Stress Criterion:
  - Stress intensities for Advanced Mark-BW fuel assembly components shall be less than the stress limits based on American Society of Mechanical Engineers (ASME) Code, Section III criteria.
- The following fuel assembly components were evaluated:
  - Guide thimble assembly
  - Top and bottom nozzles
  - Grids/grid restraint
  - Quick disconnect
  - Holddown spring assembly
  - Instrument sheath
- Positive margins were determined for all fuel assembly structural components

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Advanced Mark-BW Design Evaluation

>Fuel System Damage Criteria

- <u>Fuel Rod Cladding Stress Criterion</u>:
  - Fuel rod cladding stress shall not exceed stress limits established in BAW-10227P-A, *Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel*
    - Pm < 1.5 Sm in compression and < Sm in tension
    - Pm + Pb < 1.5 Sm
    - Pm + Pb + Pl < 1.5 Sm
    - Pm + Pb + Pl + Q < 3.0 Sm
- Types of stresses evaluated
    - Pressure (Pm)
    - Flow-induced vibration (Pb)
    - Ovality (Pb)
    - Thermal (Q)
    - Fuel rod growth (slip loads) (Q)
    - Three-point grid stop bending stresses (Pb)
    - Fuel rod spacer grid interaction (Pl)
- Positive margins were determined for fuel rod cladding stresses

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Advanced Mark-BW Design Evaluation

Advanced Mark-BW Fuel Rod Stress Result Summary

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Advanced Mark-BW Design Evaluation

>Fuel System Damage Criteria

- Cladding Strain Criterion:
  - The Advanced Mark-BW fuel rod transient strain limit is 1% for Conditions I and II events per BAW-10227P-A, *Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel.*
- Analysis conducted using BAW-10162P-A, *TACO3 Fuel Pin Analysis Computer Code*
- Calculated Linear Heat Rates for transients that result in 1% cladding strain are not limiting to plant operation

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Advanced Mark-BW Design Evaluation

>Fuel System Damage Criteria

- Cladding Fatigue Criterion:
  - The maximum fuel rod fatigue usage factor is 0.9.
- Analyzed per BAW-10227P-A, *Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel.*
- Assumed 8 year fuel rod life
- Calculated fatigue usage factor [ ]

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Advanced Mark-BW Design Evaluation

>Fuel System Damage Criteria

- <u>Fretting Criterion</u>
  - Span average cross flow velocities shall be less than 2 ft/sec
- Criterion precludes unacceptable FIV
- Mixed-core evaluations with resident fuel with and without MSMGs
- Models show small FIV amplitudes [ ]
  - Benchmark well with FIV tests

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Advanced Mark-BW Design Evaluation

> Fuel System Damage Criteria

- <u>Fretting Criterion</u>
  - Fuel assembly design shall be shown to provide sufficient support to limit fuel rod vibration and clad fretting wear.
- Extensive out-of-core testing
  - 1000 hour endurance testing @ reactor conditions
    - 0.001 inch – comparable with other proven designs
  - Dual loop FIV flow testing
    - Less than [ ] microns rms amplitude [ ]
- Successful 3 cycle LTA program (~57 GWd/mtU)
  - Included core periphery locations
- Utilize proven Mark-BW grid designs
  - [ ] failures in over [ ] rods since 1993 (only [ ] fretting)
- No failures in [ ] fuel assemblies with [ ] M5 fuel rods in [ ] reactors

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Advanced Mark-BW Design Evaluation

>Fuel System Damage Criteria

- Oxidation, Hydriding, and Crud Buildup Criterion
  - The fuel rod cladding best-estimate corrosion shall be less than 100 microns per BAW-10186P-A.
  - Hydrogen pickup is controlled by the corrosion limit.
- Predicted M5 maximum corrosion – [ ] microns
- Predicted M5 maximum hydrogen content – [ ] ppm at 65 GWd/mtU

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Advanced Mark-BW Design Evaluation

>Fuel System Damage Criteria

- <u>Fuel Rod Bow Criterion</u>
  - Fuel rod bow is evaluated with respect to the mechanical and thermal-hydraulic performance of the fuel assembly. There is no specific design criterion for fuel rod bow.
- Use of Mark-BW features consistent with existing performance data
  - New data per BAW-10186P Revision 1 Supplement 1, *Mark-BW Extended Burnup* extends rod bow database to [ ] GWd/mtU
- LTA water channel confirms rod bow characteristics
- Rod bow correlations per BAW-10147P-A Revision 1, *Fuel Rod Bowing in Babcock & Wilcox Fuel Designs* remain applicable

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Advanced Mark-BW Design Evaluation

>Fuel System Damage Criteria

- <u>Axial Growth Criterion</u>
  - Fuel assembly to reactor internals gap allowance shall be designed to provide positive clearance during assembly lifetime.
- Maximum M5 rod burnup – 62,000 MWd/mtU
- Maximum fuel assembly burnup of 60,000 MWd/mtU
- Growth models per BAW-10227P-A, *Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel*
- [ ] inch worst case gap (cold) – very conservative given low growth FA data

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Advanced Mark-BW Design Evaluation

>Fuel System Damage Criteria

- <u>Axial Growth Criterion</u>
  - The fuel assembly top nozzle-to-fuel rod gap allowance shall be designed to provide positive clearance during the assembly lifetime.
- Maximum M5 rod burnup – 65,000 MWd/mtU
- Maximum M5 fuel rod growth
- No fuel assembly growth
- [ ] inch worst case gap (hot)

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Advanced Mark-BW Design Evaluation

> Fuel System Damage Criteria

- <u>Fuel Rod Internal Pressure</u>
  - The fuel system shall not be damaged due to excessive internal pressure.
    - Limited to that which would cause the diametral gap to increase due to outward creep during steady-state operation
    - Extensive DNB propagation to occur
- Fuel rod internal pressure methodology established per BAW-10183P-A, *Fuel Rod Gas Pressure Criterion (FRGPC).*
- Internal gas pressure determined using NRC-approved TACO 3 code per BAW-10162P-A
- Fuel rod internal pressure shown to be acceptable for maximum burnup of 62 GWd/mtU
- Other NRC approved codes such as COPERNIC per BAW-10231P-A, *COPERNIC Fuel Rod Design Computer Code* may bed utilized in future evaluations

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Advanced Mark-BW Design Evaluation

> Fuel System Damage Criteria

- <u>Assembly Liftoff</u>
  - The fuel assembly holddown springs must be capable of maintaining fuel assembly contact with the lower support plate during normal operation, Conditions I and II events, except for pump overspeed transient.
  - The fuel assembly shall not compress the holddown spring to solid height for any Condition I and II event.
  - The fuel assembly top and bottom nozzles shall maintain engagement with reactor internals for all Condition I thru IV events.
- Hydraulic lift forces determined using the LYNXT code per BAW-10156P-A Revision 1, *LYNXT: Core Transient Thermal-Hydraulic Program*
  - Full core and mixed core configurations considered
- Fuel assembly shown to be acceptable

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Advanced Mark-BW Design Evaluation

>Fuel Rod Failure Criteria

- <u>Internal Hydriding</u>
  - Internal hydriding shall be precluded by appropriate manufacturing controls.
- Precluded by manufacturing controls
- Fabrication limit –[ ]ppm hydrogen
- <u>Cladding Collapse</u>
  - The predicted creep collapse life of the fuel rod must exceed the expected in-core life
- Evaluated per BAW-10084P-A, *Program to Determine In-Reactor Performance of BWFC Fuel Cladding Creep Collapse*
- M5 creep rate is [ ] that of zircaloy-4
- Creep collapse life greater than 62 GWd/mtU

Advanced Mark-BW Design Evaluation

>Fuel Rod Failure Criteria

- <u>Overheating of Cladding</u>
  - For a 95% probability at a 95% confidence level, DNB shall not occur for normal operation and anticipated operational occurrences (AOOs)
- Addressed in plant specific transient analyses with NRC approved methods
  - BAW-10199P-A Addendum 2, *Application of the BWU-Z CHF Correlation to the Mark-BW17 Fuel Design with Mid-Span Mixing Grids*

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Advanced Mark-BW Design Evaluation

>Fuel Rod Failure Criteria

- Overheating of Fuel Pellets
  - For a 95% probability at a 95% confidence level, fuel pellet centerline melting shall not occur for normal operation and anticipated operational occurrences (AOOs)
- NRC-approved TACO 3 code per BAW-10162P-A used to determine local LHR throughout rod life such that pellet centerline temperature meets criterion
- Typical generic centerline fuel melt limit is [ ] kW/ft
- Pellet Cladding Interaction
  - No generally applicable criteria
  - Clad strain and fuel melt criteria are used
- Cladding Rupture
  - Addressed in plant-specific LOCA analyses using NRC-approved methods

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Advanced Mark-BW Design Evaluation

>Fuel Coolability

- Cladding Embrittlement
  - Addressed in plant-specific LOCA analyses using NRC-approved methods
- Violent Expulsion
  - Addressed in plant-specific safety analyses using NRC-approved methods
- Fuel Rod Ballooning
  - Addressed in plant-specific safety analyses using NRC-approved methods

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Advanced Mark-BW Design Evaluation

> Fuel Coolability

■ <u>Fuel Assembly Structural Damage from External Forces Cladding Embrittlement</u>

- **Operational Base Earthquake (OBE)** – Allow continued safe operation of fuel assembly following an OBE event by ensuring that the FA components do not violate their dimensional requirements
- **Safe Shutdown Earthquake (SSE)** – Ensure safe shutdown of reactor by maintaining overall structural integrity of FAs, control rod insertability, and a coolable geometry within the deformation limits consistent with the Emergency Core Cooling (ECCS) and safety analysis
- **LOCA or SSE+LOCA** – Ensure safe shutdown of reactor by maintaining overall structural integrity of FAs and a coolable geometry within deformation limits consistent with ECCS and safety analysis

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Advanced Mark-BW Design Evaluation

>Fuel Coolability

- Horizontal analysis
  - Models and methods per BAW-10133P-A Revision 1 Addendum 1, Mark-C Fuel Assembly LOCA-Seismic Analyses
  - Core models
    - 3 to 15 FA rows
    - Full core Advanced Mark-BW
    - Mixed core of Advanced Mark-BW and resident fuel
  - Worst-case attached pipe break loadings based on leak-before-break

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Advanced Mark-BW Design Evaluation

>Fuel Coolability

- ■ Horizontal analysis results
  - Maximum grid impact loads at peripheral FA locations for shortest row
    - OBE and SSE loads within elastic limits
      - Intermediate grids – [ ]
      - MSMGs – [ ]
    - LOCA and SSE+LOCA
      - Grid deformation evaluation maintains core coolable geometry
      - Intermediate grid - [ ]
      - MSMG – [ ]
  - Maximum grid impact loads for all interior FA locations remain within elastic limits for all faulted conditions

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Advanced Mark-BW Design Evaluation

>Fuel Coolability

- Vertical analysis
  - Vertical loading analysis methodology per BAW-10133P-A Revision 1
  - Bounding attached pipe breaks based on leak-before-break
  - Guide thimble loads well below allowable buckling load limits for rod insertability

    [ ]

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Advanced Mark-BW Design Evaluation

>Conclusion

- Advanced Mark-BW fuel assembly meets all fuel assembly design criteria critical to safe and reliable operation.
- The standard Mark-BW features maintained in the Advanced Mark-BW assembly provide reactor-proven design parameters that provide a basis for successful future performance.
- Design verification testing and analyses have demonstrated the acceptability of the added design features and ensure that the Advanced Mark-BW fuel assembly will operate safely and reliably.
- A detailed LTA program further verified the Advanced Mark-BW irradiation performance.
- Acceptable Advanced Mark-BW fuel assembly and fuel rod mechanical and thermal-hydraulic performance capability can be obtained for fuel rod burnups up to 62,000 MWd/MTU.

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